Estuarine Management and Technologies Journal

Estuarine Management and Technologies 1(1): 39–56 (2024)
DOI: 10.3897/emt.1.119588

Research Article

Factors affecting scum formation and the use of electronic nose to identify fundamental odor properties in urban estuaries

Joan Cecilia Casila[1], Ryohei Okuyama[2], Katsuhide Yokoyama[3]

1 *Land and Water Resources Engineering Division, IABE, CEAT, University of the Philippines, Los Baños, Philippines*
2 *Toyo Engineering Corporation, Chiba, Japan*
3 *Department of Civil and Environmental Engineering, Tokyo Metropolitan University, Tokyo, Japan*

Corresponding author: Katsuhide Yokoyama (k-yoko@tmu.ac.jp)

Abstract

The foul odor of rivers is often linked to poor water quality and unhealthy air. In this study, variations in water quality and hydrodynamics near the confluence of the Shakujii and Sumida Rivers in Tokyo, Japan, were monitored, and their effects on sum generation were analyzed. The Shakujii River, facing scum and odor issues, was monitored hourly for on-site scum coverage. Samples of scum, sediment, and water were collected and subjected to odor analysis. The odor characteristics were assessed using an electronic nose odor machine and then correlated with human olfactory sense. Results indicated that salinity, dissolved oxygen (DO), rainfall, sediment, and topography influenced scum formation. Scum coverage was higher when salinity was below 1 psu and DO was below 6 mg/L. Organic acids (14.2%) and hydrogen sulfide (14.4%) were the primary odor components of sediment in the Shakujii River. In the Sumida River sediments, organic acids (4%) and sulfurs (1%) were prominent. The Shakujii River sediment exhibited the highest odor index and showed a 62.43% similarity with scum. These results could support efforts to address scum and odor issues in the area. They could provide new insights into on-site formation based on actual river hydrodynamics and water quality variations.

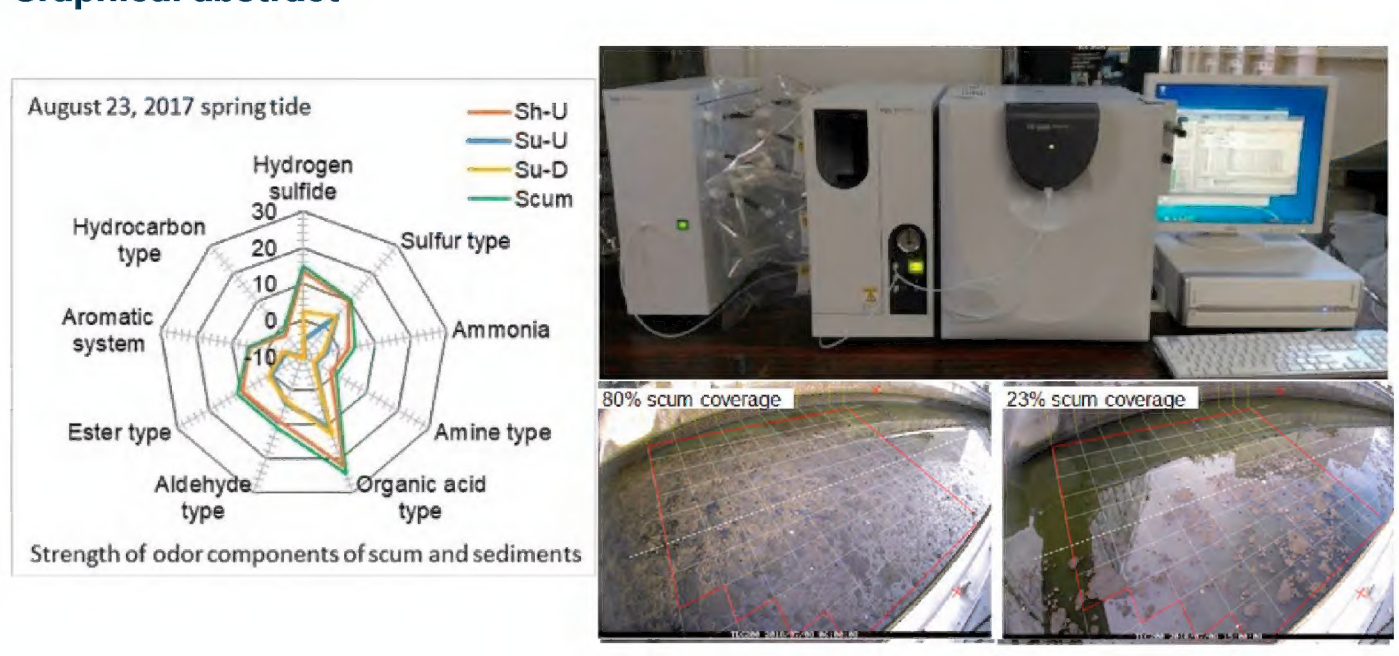
OPEN ACCESS

Academic editor: Priya K L
Received: 26 January 2024
Accepted: 22 May 2024
Published: 7 June 2024

Citation: Casila JC, Okuyama R, Yokoyama K (2024) Factors affecting scum formation and the use of electronic nose to identify fundamental odor properties in urban estuaries. Estuarine Management and Technologies 1: 39–56. https://doi.org/10.3897/emt.1.119588

Copyright: © Joan Cecilia Casila et al.
This is an open access article distributed under terms of the Creative Commons Attribution License (Attribution 4.0 International – CC BY 4.0).

Graphical abstract



Key words: Estuary management, River odor, Salt intrusion, Shakujii River, Sumida River

Introduction

The electronic nose (e-nose) technology has been increasingly utilized for various purposes. It uses the principle of olfactory sense to complete qualitative and quantitative analyses of gases or odors and distinguish complex volatiles that reproduce the structure (Rahman et al. 2020; Arakawa et al. 2022). Its application in food industry, environmental detection, military defense, NASA space programs, and medical treatment have expanded. In the military, e-nose allows the detection of explosives to save lives, track odorants being propagated through aerosol transmission, and for potential methods to improve combustion efficiency (Nagappan et al. 2017). The e-nose method could also be used for pollution monitoring. Wang et al. (2023) used the portable electronic nose PEN3, equipped with ten different heated metal sensors, to analyze its applicability, feasibility and application scenarios for the detection of typical odorants in water samples. The e-nose technology was also employed to study a polluted urban river often in black color and emits a foul odor, the Yueliang River in Huzhou City (Qiu et al. 2021). The technology was found to be a fast, easy-to-build, and cost-effective detection system for black-odor river monitoring.

Foul river odors produce various undesirable reactions, from annoyance to documented health effects. Odor significantly impacts the quality of life and often triggers complaints from individuals residing near rivers. While there is no known toxicological-sanitary risk associated with odor, it is frequently linked to poor water quality conditions and 'unhealthy' air (Akcaalan et al. 2022).

In the tidal areas of small- to medium-sized rivers in Japan like the Shakujii, Nomi and Nihonbashi, residents complain about foul odor emanating from accumulated scum. Scum forms as the organic sludge deposited at the river bottom rises with anaerobic gas (Inagawa et al. 2020). Some of the sludge or mud deposits are made up of unusually compact black mud, an indication of the development of anoxic conditions in surficial sediments (Murat et al. 2016). Several studies have outlined the scum generation mechanisms, such as organic sludge buildup in sewer pipes during rainstorms and occurrence under low dissolved oxygen (DO) conditions (Okuyama et al. 2018). Oxygen depletion posed a serious environmental concern in the Sumida River estuary. Massive fish deaths in the tidal reach of small urban rivers in the Sumida and Kanda River basins have been reported due to low DO conditions (Kaneko and Nihei 2012; Sado-Imamura and Fukushi 2018). These conditions frequently appear just after flooding events in summer with combined sewer systems identified as potential sources of odorous pollution.

Although the mechanisms of scum occurrence have been studied separately, few studies integrate salinity intrusion, and hypoxic water mass flow with the mechanism of scum generation and foul odor in river estuaries. Scum formation were mostly studied in the laboratory under different wind conditions (Wu et al. 2024a) and for confirmation of its emergence a few hours after anaerobic reactions (Miura et al. 2017). Pertaining to odor, it was observed that the anaerobic gas generated from the bottom sludge contains 67% methane (CH_4) and carbon dioxide (CO_2), with a few traces of hydrogen sulfide (H_2S) (Miura et al. 2018). The common industrial H_2S gas has an odor threshold magnitude lower than levels known to cause symptoms by classical toxicologic or irritative mechanisms; however, these gases are often associated with "annoyance"

and symptom reporting at levels that barely exceed their odor thresholds (Batterman et al. 2023). Although measured gas concentrations may not precisely reflect human olfactory perception, comprehensive studies correlating the e-nose technology or odor machine results with human smell tests are needed to characterize scum-generated odor properly.

Despite efforts to maintain water quality parameters within standards, river odor persists. The TY River in Jiangsu Province is suffering from complex odor problems and poor water quality (Guo et al. 2021). A comprehensive study on characterizing the odors and odorants in TY River was conducted that successfully identified odor-causing compounds like sulfides, phenols, benzene to name some and relate them to odor types, including earthy, marshy, fishy, woody, medicinal, and chemical odors. The application of the odor emission capacity (OEC) as a surrogate parameter in the assessment of river water quality was studied by Pandan et al. (2017). The relationship between odor status and the traditional analytical parameters used in the assessment of ecological status, showed a strong relationship between the organic content in the river samples in Italy and their odor in terms of OEC. OEC can be easily integrated into the assessment protocol and is a good subrogate indicator for the assessment of river water quality. Scum and odor situations occur in highly developed countries, and in the future, developing countries may experience the same problem even if water quality standards are met.

This paper aims to analyze the factors influencing scum formation in actual river locations. The salinity and DO variations in the confluence of the Shakujii and Sumida Rivers have been studied to understand their possible effects to scum and odor. The study utilized the electronic nose technology or odor machine as a reliable and repeatable method, to determine the odor properties of scum, water, and bottom river sediments The strength of the odor of the measured samples was determined, and the similarities of the odor components were identified. Comparison of the strength of smell representation or odor components allowed identification of potential odor sources. The study is significant since many rivers have problems with odor and scum generation. The mechanics of scum formation could aid in better solutions and policy enforcement to enhance river water quality.

Materials and methods

Study area

The Shakujii River Basin has an average annual rainfall of 1368 mm over 43 years. The average maximum daily rainfall is 121 mm and the average maximum hourly rainfall is 40.4 mm (Japan Meteorological Agency). The source of the water in the Shakujii River (Fig. 1b) is Kogane City, Tokyo. The watershed area is 61.6 km^2, the river length is 25.2 km, and the estuary length is approximately 1.4 km (Fig. 2b). The elevation difference of the watershed is 85 m, and the average topographic gradient is approximately 1/340. The river features concrete-lined channels in the urban and residential downstream areas, with a width of approximately 20 m shore protection height of approximately 7 m, and 154 combined sewer outfall chambers draining domestic and storm water runoff.

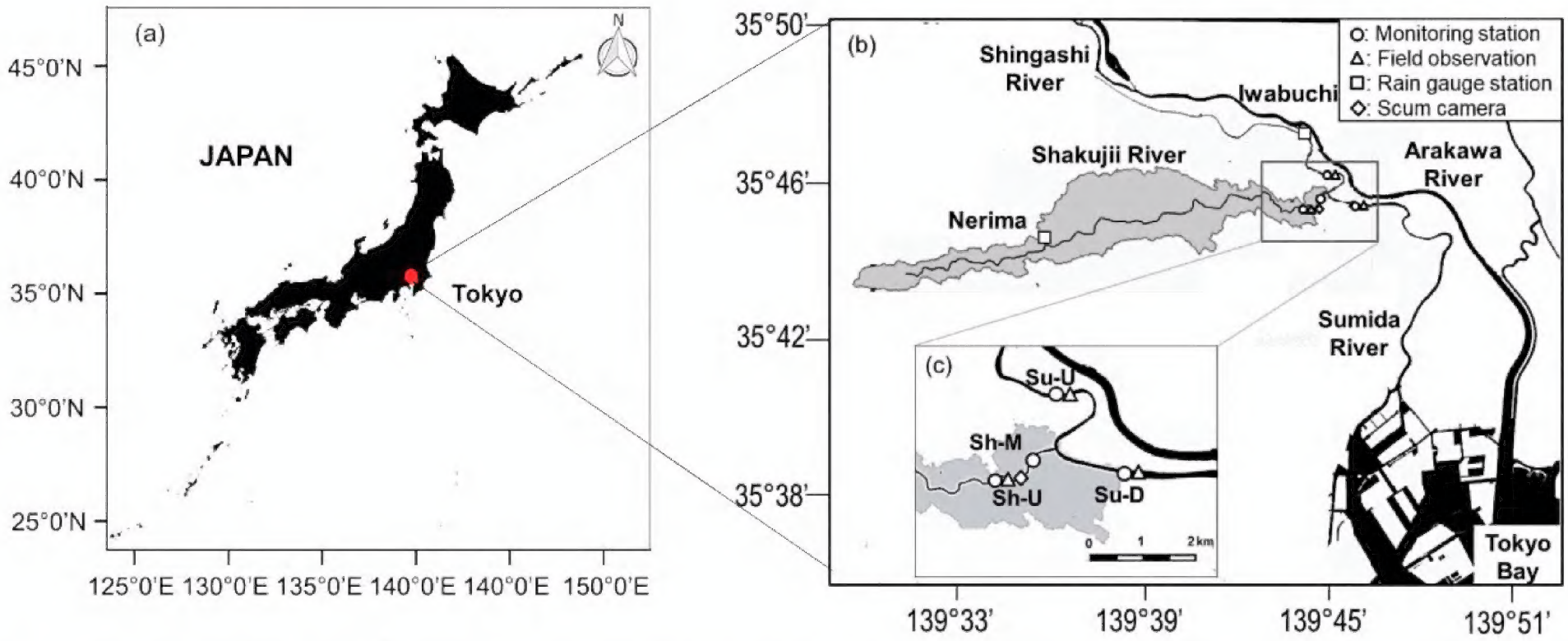


Figure 1. (**a**) Location of the Shakujii and Sumida Rivers relative to Tokyo Bay (**b**) Location of the Nerima weather station and Iwabuchi sluicegate weather station (**c**) Water quality monitoring stations: Shakujii upstream (Sh-U), Shakujii mid-stream (Sh-M), Sumida upstream (Su-U) and Sumida downstream (Su-D).

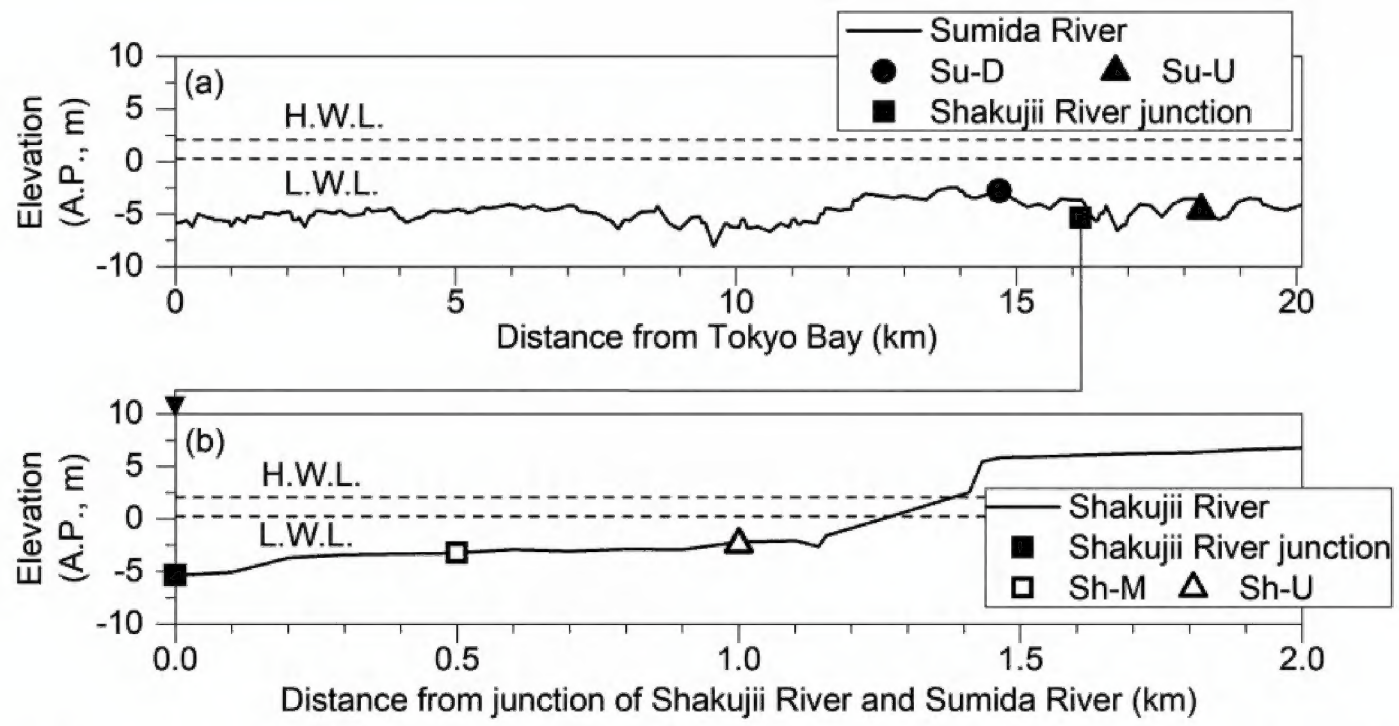


Figure 2. Station location and longitudinal topography in Arakawa Peil (A.P., m) elevation of the (**a**) Sumida River and (**b**) Shakujii River.

The Sumida River estuary is located on the west side of Tokyo Bay and flows through the deltaic lowland of central Tokyo. It receives fresh water from the Arakawa River, Shingashi River, Shakujii River and Kanda River, which all empty into Tokyo Bay. The location of the upstream and downstream edges of the river, with a length of 20.4 km, is near the Iwabuchi sluice gate and around the lower area of Tsukiji Market, respectively (Fig. 1b). The drainage basin covers approximately 690 km^2, receiving water from various tributaries including the Shingashi River, Kanda River, and Shakujii River. The Sumida River is characterized by a general river slope (Fig. 2a) that promotes stagnant areas and a large effect of sea water that goes landward, and 60% of the river water is from treated sewage water (Taniguchi 1999; Japan River Restoration Network (JRRN) 2012). The confluence of the Shakujii River and the Sumida River is located 16.5 km from Tokyo Bay.

This study was conducted in the Shakujii River upstream (Sh-U) and midstream (Sh-M) stations and in the Sumida River upstream (Su-U) and downstream (Su-D) stations (Fig. 2). The riverbed elevations of the stations were as follows: Sh-U

is -2.68 A.P. m, Sh-M is -3.34 A.P. m, Su-U is -4.88 A.P. m, and Su-D is -3.58 A.P. m. The upstream Sumida River station has a deeper riverbed elevation than the downstream station. Additionally, the intertidal zone in the Shakujii River estuary faces a steep slope like a wall near Sh-U where high tide is not transited, and the length of the waterbody does not change from low tide to high tide.

Water quality monitoring

Water quality parameters were monitored at three observation stations: Sh-M, Su-U and Su-D (Fig. 2c). Data were measured at 10 minutes interval using a water level sensor (HOBO, U-20 water level logger), salinity sensor and DO sensor (JFE Advantech, Infinity-ACTW, ACLW, AROW). The sensors were attached to the revetment wall 1 m from the riverbed. The data used for the Sh-U station were obtained from the Kita Government Office. The data from Aug. in the summer of 2017 to Oct. in autumn of 2017 were used for the analysis. The rainfall intensity (mm/hr) used in this study were the average of the data from the Iwabuchi (Ministry of Land, Infrastructure, Transport and Tourism, MLIT) and Nerima (Japan Meteorological Agency) weather stations.

Scum coverage

The water surface in Sh-U, located upstream of the tidal area, is monitored for several reasons by the Kita City Office, Tokyo using a fixed video camera. A fixed camera allows daily monitoring of the scum occurrence in a location, evaluation of alternative technologies or management practices in terms of their effectiveness in reducing odor impacts, documentation of specific events or episodes that may provide significant information regarding scum and odor occurrence, identification of specific odor sources within a community or a particular facility, and verification of complaints.

In this study, an area of 25 m in length and 20 m in width was divided into 100 grids of 2.5 × 2 m (Fig. 3). The percentage of the area covered by scum in a grid was identified visually for an interval of one hour. Then, scum coverage was

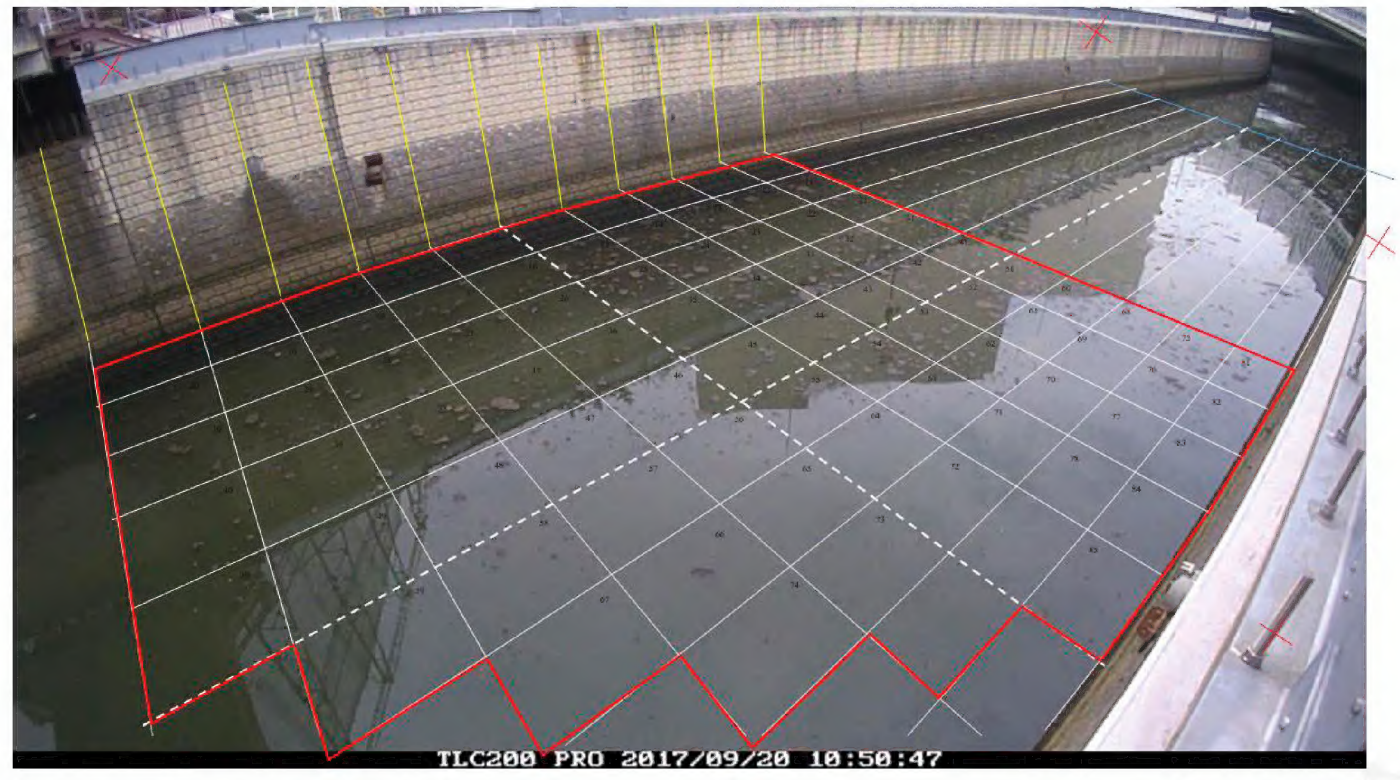


Figure 3. Fixed camera image of 5% scum coverage in Sh-U on September 20, 2017 overlaid with a 25 m × 20 m scum coverage counting grid.

obtained as the total percentage of each grid. The scum coverage data in Sh-U from June to October 2017 were analyzed. The scum coverage data were classified according to DO ranges of 0–1 mg/L, 1–2 mg/L, 2–4 mg/L, 4–6 mg/L and > 6 mg/L. A boxplot was made to determine the descriptive statistics as follows: minimum, median, maximum, lower quartile and upper quartile values. The scum probability for each DO range was also computed using Eq. (1).

$$\textit{Scum probability} = n/N \tag{1}$$

where n is the number of events with scum in a particular DO range, and N is the total number of populations or data with and without scum in the DO range.

Odor analysis

Sampling

The river water and scum were collected using a bucket while the bottom sediment was obtained using a grab sampler. The samples were transferred to glass bottles and plastic bags and transported to the laboratory for odor analysis. The sampling was conducted on Aug. 23, 2017, spring tide, in Sh-U, Su-U and Su-D. The samples were stored in a refrigerator at 5 °C. The samples were transferred to a special sampling bag, pumped with nitrogen and allowed to sit for 2 hours. The air from the sample was then transferred to another sampling bag, which was inserted into the machine for odor analysis.

Odor machine utilizing the concept of electronic nose

Analytical instrumentation has been previously used for the identification and quantification of chemical compounds present in malodorous emissions from both sewers and wastewater treatment plants (WWTPs). These techniques have the advantages of objectivity, repeatability and accuracy (Muñoz et al. 2010). A Fragrance and Flavor Analyzer (Shimadzu Corporation, FF-2020) was used for odor analysis (Fig. 4a). In this machine, a gas sample is passed through 10 metal oxide semiconductor sensors. When the gas contains an odorous component, the result is a characteristic resistance change of the sensor, expressed as vector values (Kita and Toko 2014).

The calibration was performed by allowing 9 reference gases in bottle containers (Fig. 4a) to pass through the 10 sensors (Fig. 4b). The calibration outputs were the 9 vector values. When air samples were analyzed, the sample bags were directly attached to the machine for analysis. However, scum, sediment and water samples were initially diluted in nitrogen, which is a standard procedure for the machine. Nitrogen is an odorless inert gas that does not undergo chemical reactions and therefore does not affect the gas sample. After sample preparation, the sample bags containing air were attached to the machine, and the analysis resulted to another vector values. As an analytical procedure, the calibrated and gas sample vector values were compared to determine the similarity index and strength of each odor component. The analog value of the odor index was generated from the strength of odor representation.

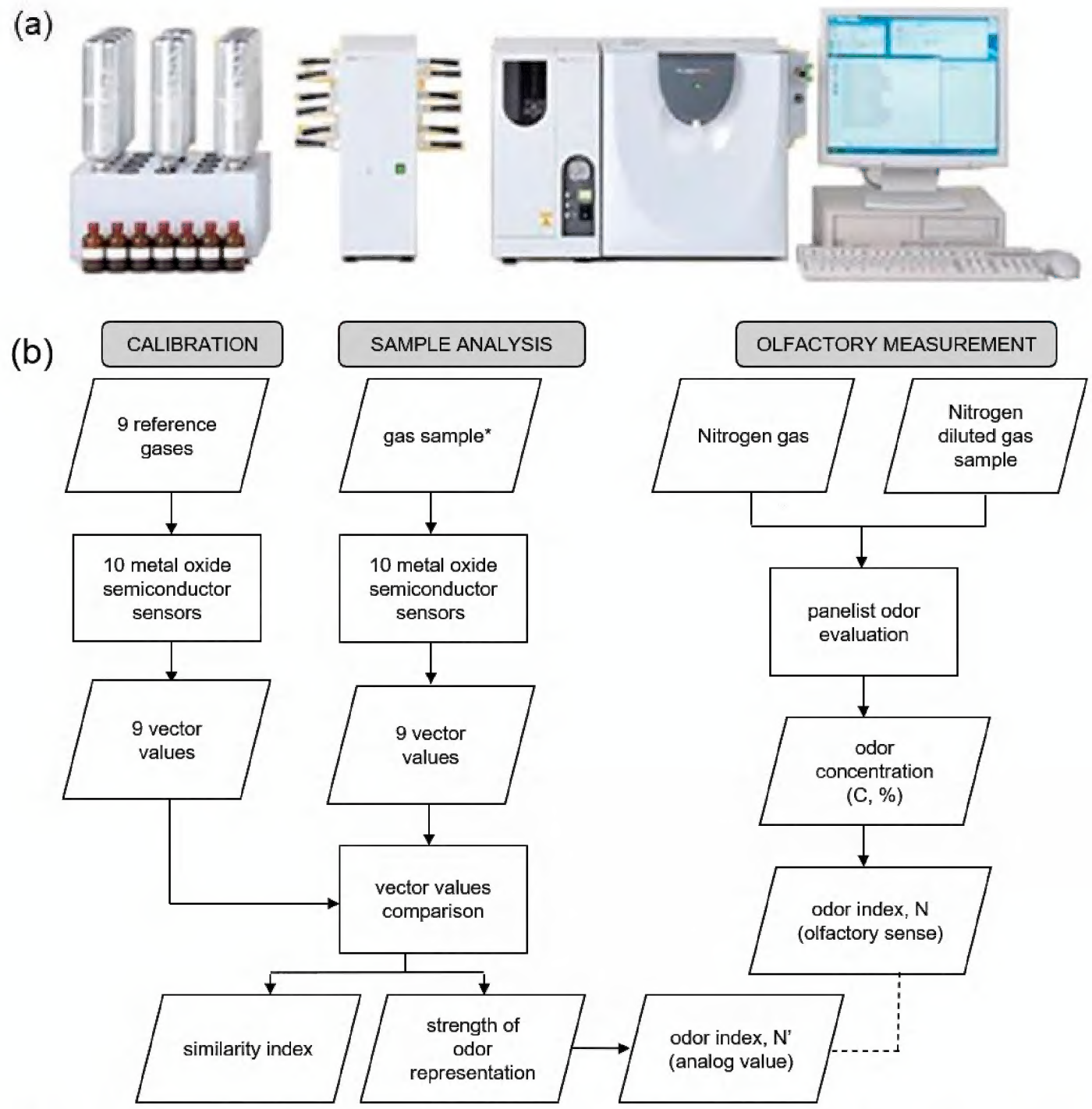


Figure 4. (**a**) The Fragrance and Flavor Analyzer system and (**b**) schematic diagram of odor machine calibration, gas sample analysis and olfactory measurement.

Olfactory measurement and odor index

The odor concentration is the maximum dilution after distinguishing and comparing two samples through the olfactory method. A simple olfactory measurement was performed following the Ministry of the Environment method (Ministry of the Environment 2019). The panelists compared an odor sample diluted with nitrogen and a sample of nitrogen gas only. The odor concentration result given by the panelist was then converted to the actual olfactory sense herein referred to as the odor index. The odor index is the total strength of the odor and was calculated as the logarithm of odor concentration given by Eq. (2):

$$N = 10 \log C \quad (2)$$

where N is the odor index, and C is the odor concentration.

The odor machine generates an analog value of the odor index. The odor index is the sum of the strength of odor representation. The strength of odor representation or odor components is equal to the length of the sensor vector multiplied by each similarity index (Casila et al. 2019b). The analog value from the machine was converted into the actual olfactory sense odor index through

an equation. The regression equation from the analog value of the odor index to the odor index was calculated with Eq. (3).

$$N = 1.0837\,N' \tag{3}$$

where N is the odor index and N' is the analog value of the odor index.

Results and discussion

Meteorology and tides

The temporal variations in rainfall, water level, salinity, DO, and scum coverage are shown in Fig. 5. Neap tides occurred on Aug. 31, Sep. 15 and Sep. 29, while spring tides took place on Aug. 23, Sep. 7, Sep. 21 and Oct. 5, all in the year 2017. There were five rainfall events with intensities greater than 5 mm/hr. The highest daily rainfall, recorded on Sep. 17, had a peak intensity of 12 mm/hr and a total amount of 65 mm. The effects of the tides and rainfall on the water quality parameters were analyzed.

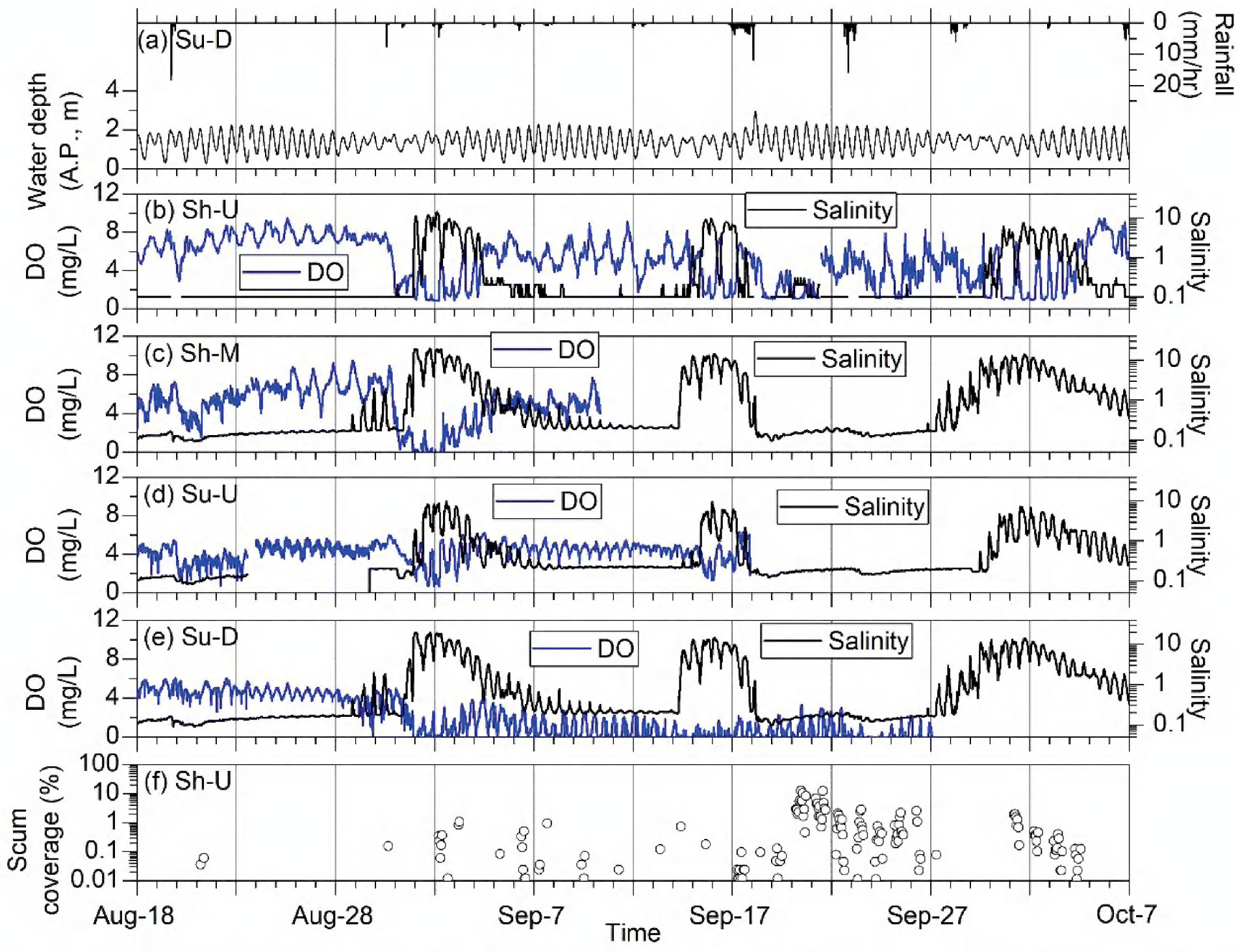


Figure 5. Time series from Aug. 18 to Oct. 7, 2017, showing: (**a**) water depth (A.P., m) in Su-D and average rainfall value (mm/hr) from Iwabuchi and Nerima weather stations; DO (mg/L) and salinity at stations: (**b**) Sh-U, (**c**) Sh-M, (**d**) Su-U, and (**e**) Su-D; and (**f**) scum coverage (%) at Sh-U.

Saltwater intrusion

The salinity in the estuaries increased during neap tide and decreased during spring tide, which is a common estuarine condition (Uncles 2002). Salinity was minimal during intermediate tide following the spring tide in the two rivers. Salinity during neap tide was highest in Su-D, followed by Sh-M and Sh-U, and was lowest in Su-U (Fig. 6b–e). The lengths of the stations from the river mouth were 14.7 km in Su-D, 16.65 km in Sh-M, 17.15 km in Sh-U and 18.3 km in Su-U (Fig. 2). The salinity decreased with the distance of the stations from the river mouth. Two salinity peaks were observed in Su-D during neap tide due to the semidiurnal nature of these tides. However, three salinity peaks occurred in Su-U, Sh-U and Sh-M during neap tide in the semidiurnal tidal cycle. The probable sources of salinity were saltwater from Tokyo Bay and residual salinity at the confluence of the Shakujii and Sumida Rivers.

The intrusion of unoxygenated saltwater from Tokyo Bay is important to investigate. The hypoxic conditions (< 2 mg/L) at the bottom depth may contribute to odor occurrence. Salinity was notably higher one or two days after neap tide (Okuyama et al. 2018) and decreased as tidal range increased (Fig. 5). The salinity sensors measured the bottom layer salinity. Therefore, it is estimated that a stratified salt wedge was formed by the vertical density stratification of salinity and freshwater. In the Chikugo River, the salinity was stratified during neap tide, and salinity intrusion occurred at tidal ranges of less than 1.5 m. The peak salinity occurred two days after neap tide, and the stratification changed, with waters becoming well mixed at spring tide (Somsook et al. 2020). Studies in the Sumida River on September 2008 (Nihei et al. 2009) and July 2017 (Casila et al. 2019a) observed a salt wedge during neap tide and well mixed salinity during spring tide, suggesting that seawater from Tokyo Bay formed a salt wedge during neap tide, which flowed through the Sumida River, causing salinity intrusion to the Shakujii River.

Saltwater movement in the confluence of two rivers

Fig. 6 shows the temporal variation in salinity at the four stations during Sep. 2 neap tide. Span 1 (in red for all stations) occurred during high tide, indicating high salinity after saltwater intrusion from Tokyo Bay, carrying water with low DO. The first high tide started at approximately 0:00 in the Sumida River. Salinity intrusion was evident at high tide with a peak value of 19.0 in Su-D at 02:30, 2 hours after high tide. In Su-U, salinity increased at 00:30 and peaked with a value of 8.6 at 05:00. In Sh-M, salinity increased rapidly at 01:00, with a peak value of 17.1 at 03:30. In Sh-U, salinity increased rapidly at 0:00, with the highest salinity value of 14.2 recorded at 03:00. Span 2 (in blue), which occurred during ebb to low tide, showed the influx of freshwater with high DO and low salinity after rainfall. Higher DO levels were observed upstream at Sh-U and Su-U. Saltwater was transported seaward during low tide at 9:00 in Su-D. The lowest salinity value in Su-D was 4.9 at approximately 12:00, 3 hours after low tide. In Su-U, Sh-M and Sh-U, salinity decreased during low tide due to freshwater influx.

Span 3 (shown in yellow in Sh-U, Sh-M and Su-U and in red in Su-D) indicates the first salinity peak during the flood tide of the next tidal cycle. In Sh-U, Sh-M and Su-U, salinity started to increase at approximately 11:00 due to the residual

salinity moving landward. The peak salinity values were 7.4 at 12:00 in Sh-U, 9.9 at 11:30 in Sh-M, and 9.9 at 14:00 in Su-U. The values of peak salinity in Sh-M and Su-U were the same. Sh-M had an earlier peak because it was closer to the confluence. The confluence has the deepest bed elevation of -5.36 A.P. m, which caused salt retention. The Sh-U has a bed elevation of -2.68 A.P. m, while Sh-M has a bed elevation of -3.34 A.P. m. The bed slope is inversely graded from Su-D to areas upstream with a bed elevation of -4.88 A.P. m for Su-U and -3.58 A.P. m for Su-D (Fig. 2). Therefore, it is estimated that at the moment of change from ebb tide to flood tide, the direction of the flow changed in span 3. A pressure wave towards the upstream direction occurred and pushed the salinity that remained at the lowest point (Fig. 6f). In Su-D, there is no span 3, which means that residual salinity does not exist. Salinity increased and reached a peak value of 13.3 at 18:00, 2 hours after high tide. The time difference in peak salinity at Su-D and that of the other stations for Span 3 suggests that Su-D is largely affected by the salt wedge from Tokyo Bay. The lag time for salinity intrusion in Su-D may have also been because the low velocity during neap tide caused the salt wedge to move slowly. Span 4 (in red) showed a second salinity peak. The peak salinity in Sh-U was 9.4 at 18:00, 11.1 at 17:30 in Sh-M and 7.7 at 16:00 in Su-U. At the three stations, it was observed that salinity peaked two times for one tidal cycle during other neap tide events with or without rainfall (Fig. 5). Salinity moves seaward during ebb tide. It is noteworthy that the start and end times for Spans 3 and 4 in Sh-U and Sh-M were the same.

Effect of salinity and topography in scum formation

From the results, two salinity peaks were observed for one tidal cycle in the Shakujii River tidal area where scum is mainly generated. The channel slope from Sh-U to Sh-M is almost zero. This unique topography is a significant contributing factor to scum development. Sh-U also faces a steep wall that does not allow water transit during high tide. These factors could promote stagnant water conditions, which are conducive to scum generation

Higher salinity brings higher hydrogen sulfide which could be generated from the reduction of sulfate from seawater. This inhibits methane formation causing stronger odor but less scum formation. The odor index and odor concentration will be discussed in the succeeding section. Good estuary mixing is therefore favorable to avoid scum formation.

DO fluctuation

Among the four water quality monitoring stations, DO was consistently lowest in Su-D (Figs 5e, 6). Hypoxic water of less than 2 mg/L was observed in Su-D during neap tide except when there was an influx of freshwater after rainfall (Fig. 6e). In Su-U, the DO level was approximately 4 mg/L most of the days, but levels decreased to less than 2 mg/L when salinity increased during neap tide. The same trend was also observed in Sh-U and Sh-M. The DO levels in the Shakujii River can exceed 8 mg/L, but the levels decrease to less than 2 mg/L during neap tide. The factors that contribute to the decline in DO in the Shakujii River are rainfall and tidal level. The DO in Sh-U decreased from 5 mg/L to 1 mg/L for 12 hours after rainfall on Sep. 18 and from 6 mg/L to 1 mg/L for 24 hours from

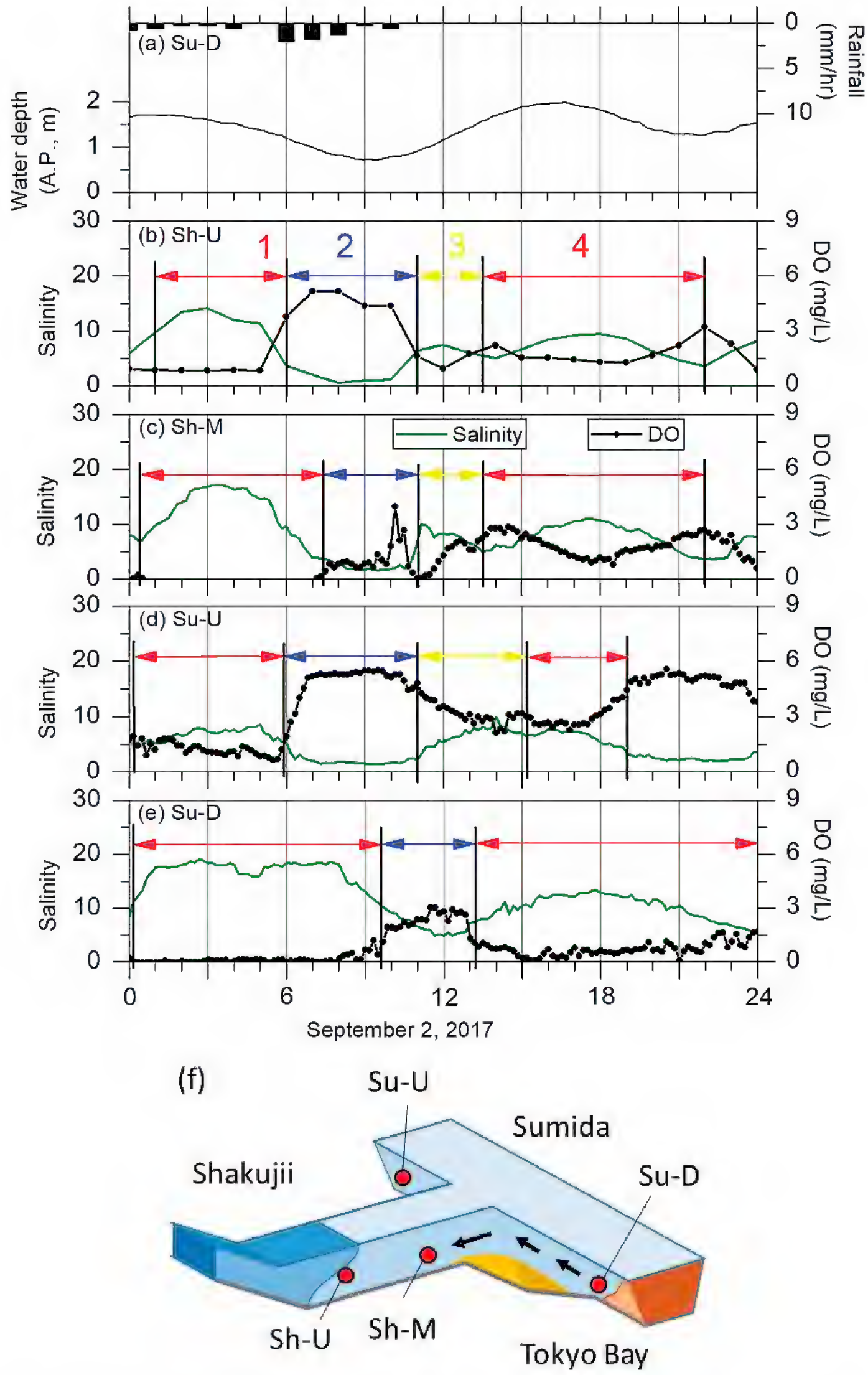


Figure 6. Time series of (**a**) tidal level in Su-D and rainfall; salinity and DO in (**b**) Sh-U, (**c**) Sh-M, (**d**) Su-U, and (**e**) Sh-U on the Sep. 2, 2017 neap tide. Spans 1, 2, 3 and 4 are indicated in red, blue, yellow and red, respectively. (**f**) The residual salinity in the confluence and the saltwater from Tokyo Bay.

Sep. 23 to 24 (Fig. 5b). The DO increased due to rainfall and decreased thereafter during the two rainfall events on Sep. 18 and Sep. 23. DO must have been consumed for the decomposition of organic matter, which was similar to the findings of a study conducted in the Shakujii River (Casila et al. 2017).

The semidiurnal tidal cycle caused recurrent DO fluctuations in the Sumida and Shakujii Rivers, which were evident as repeating DO trends. Although both rivers are affected by tide, the DO trend in the Shakujii River was different from that in the Sumida River. The DO was low (in Su-D and Su-U) during high tide due to saltwater intrusion, while DO was high (in Su-D and Su-U) during low tide due to freshwater influx from upstream tributaries. The DO fluctuated largely during neap, spring and intermediate tides in the Shakujii River (Fig. 5b, c).

Effect of rainfall and DO on scum coverage variation

From Sep. 20 to 26, scum appeared 3 days following heavy rainfall with a total of 64.75 mm and a maximum intensity of 3.75 mm/hr (Fig. 5). On Sep. 20, the hourly scum coverage ranged between 0.5 and 12.9% (Fig. 3). Scum tends to appear two or three days after rainfall (Miura et al. 2018). Rainfall is therefore the main precursor to scum generation. The current data set indicates minimal scum coverage (less than 1%) when rainfall was 30 mm and 65 mm. Odor detection during field observation was heightened when scum coverage exceeded 5%. The water surface exhibited large portions of scum when the coverage surpassed 10%.

Scum in the Sh-U station started to appear on Sep. 2 (DO = 0.83–5.18 mg/L and salinity = 0.5–11.4) during neap tide, 2 days after rainfall, but the coverage remained under 1% (Fig. 5). Other instances of less than 1% scum coverage occurred on Sep. 3 (DO = 1.6–2.07 mg/L and salinity = 5.5–5.2) and Oct. 1 (DO = 2.82–6.97 mg/L and salinity = 0.2–1.8) during neap tide. Scum becomes more apparent when coverage exceeds 1%. The events with more than 1% coverage were observed from Sep. 20 during spring tide (DO = 1.04–2.66 mg/L and salinity = 0.2–0.3) to Sep. 26 during intermediate tide (DO = 2.15–4.02 mg/L and salinity = 0.1). Minimal salinity levels in the Shakujii River were recorded during the intermediate tide following the spring tide. Higher scum coverage was apparent when DO and salinity were low, typically occurring in the Shakujii River during spring tide. The low DO levels were likely due to OM decomposition, with high levels of OM possibly discharged from the combined sewer systems. Higher salinity resulted in reduced scum coverage, suggesting a limiting effect of salinity on scum and odor production.

Relationship between DO, scum coverage, and scum probability

The relationship between DO, scum coverage, and scum probability is shown in Fig. 7. The data gathered from June to Oct. 2017 at the Sh-U station where scum presence was apparent, indicated higher scum coverage at lower DO levels. Under hypoxic conditions of 0–1 and 1–2 mg DO/L, the median and upper quartiles (50–75% events) showed a scum coverage exceeding 1%. At approximately 0–1 mg/L DO, under anoxic conditions, the scum probability reached 75%. The scum probability was nearly identical for DO concentrations of 2–4 mg/L and 4–6 mg/L, which were 24% and 22%, respectively. It was observed that scum generation is inhibited with increasing DO levels, as scum probability decreased to 12% when DO exceed 6 mg/L. Additionally, the DO range of > 6% had the narrowest interquartile range compared to other DO ranges. It is recommended that DO levels ≥ 5 mg/L for Class B and C rivers, or ≥ 7.5 mg/L for Class A rivers, be strictly mandated to protect the environment.

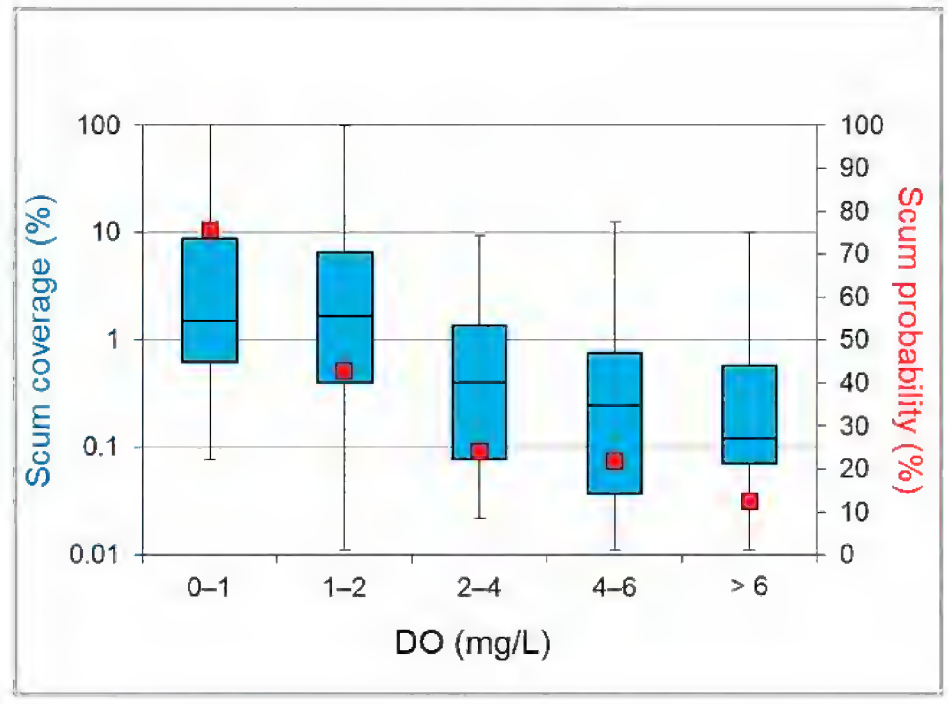


Figure 7. Scum probability and relationship between scum coverage (%) and DO (mg/L) in Sh-U for 2017 data.

Most research on scum and odor has focused on wastewater treatment plants (Wang et al. 2016; Akcaalan et al. 2022), single rivers (Müezzinoğlu et al. 2000; Guo et al. 2021), and shallow eutrophic lakes (Xu et al. 2007; Wu et al. 2024b), with limited quantitative studies and on-site estuarine dynamics related to scum generation and odor.

Odor index and components

The results of odor analysis for scum, sediment and water samples are presented in Table 1. The scum sample from July 5, 2017 closely resembles the common brown and buoyant anaerobic sludge, serving as basis for comparison. The sediment and water samples were collected on the Aug. 23, 2017, during spring tide. The odor index was highest for scum, followed sediment and water. The Sh-U sediment had the highest similarity to scum, followed by Su-D sediment. The odor concentrations reported by the panelists ranked similarly, with scum at the highest, followed by sediment and water. The conditions in Sh-U on July 5 included a salinity of 0.1 and DO levels ranging from 1.6–6.7 mg/L, averaging4.2 mg/L at the time of scum appearance. Scum was not present in

Table 1. Comparison of the odor and characteristics of scum, sediment and water samples.

Station	Date	Sample	Odor index	Odor concentration	Similarity with scum	Appearance	Olfactory feature
Sh-U	July 5, 2017 (intermediate going spring tide)	Scum	27.8	597.7	-	Brown: contains a lot of water, very soft and easy to disintegrate	Sour pungent odor
Sh-U	Aug. 23, 2017 (Spring tide)	Sediment	25.5	353.7	62.4	Black: sand of approximately 5 mm and sticky mud	Sour pungent odor
		Water	1.4	1.4	0	Transparent: slight suspended matter	Odorless
Su-U	Aug. 23, 2017	Sediment	15.3	21.2	0	Gray: particles were very small and silty clay	Slight fishy smell
		Water	1.3	1.4	0	Transparent: slight suspended matter	Odorless
Su-D	Aug. 23, 2017	Sediment	13.3	33.7	25.5	Gray surface layer, black bottom layer: very small particles and silty clay	Slight fishy and sour smell
		Water	-	-	-	-	-

Sh-U on Aug. 23, despite the DO ranging from 6.6–9 mg/L and salinity of 0.1, likely because there was no rainfall 2 to 3 days prior.

Fig. 8 shows the odor components of the July 5 scum sample from Sh-U and the Aug. 23 sediment samples from Sh-U, Su-U and Su-D. The prominent components of the odor from scum and sediment samples in the Shakujii River (Sh-U) were organic acid and hydrogen sulfide. This was followed by aldehyde type, ester type and sulfur type compounds out of the 9 reference gases. Organic acid and sulfur compounds were prominent in Su-U and Su-D sediments. These odor components resemble those from sanitary sewage discharged by combined sewer systems during heavy rainfall. Organic acid comes from automobile emissions and anthropogenic sources such as wood, agricultural waste and fossil fuels (Sun et al. 2016). Ester is derived from acids like animal fat or vegetable oil. Hydrogen sulfide is generated from the reduction of sulfate from seawater and anaerobic decomposition of sulfur-containing proteins and organic matter. The sulfur compounds in the scum primarily come from sulfur-containing organics in the wastewater from restaurants, households, and other facilities (Ma et al. 2016). This finding was similar to the findings of Guo et al. 2021 where odor-causing compounds particularly sulfides where identified and related to marshy odor. Scum did not usually appear in the Sumida River stations. This was probably because the area had higher salinity than Sh-U. This may also explain the lower odor strength values of the Sumida River stations. Salinity during spring tide was higher in the Sumida River than in Sh-U (Fig. 5). High salinity inhibits the generation of methane, which is an anaerobic gas that is highly associated with scum generation (Miura et al. 2018). Scum coverage is usually high when salinity is low.

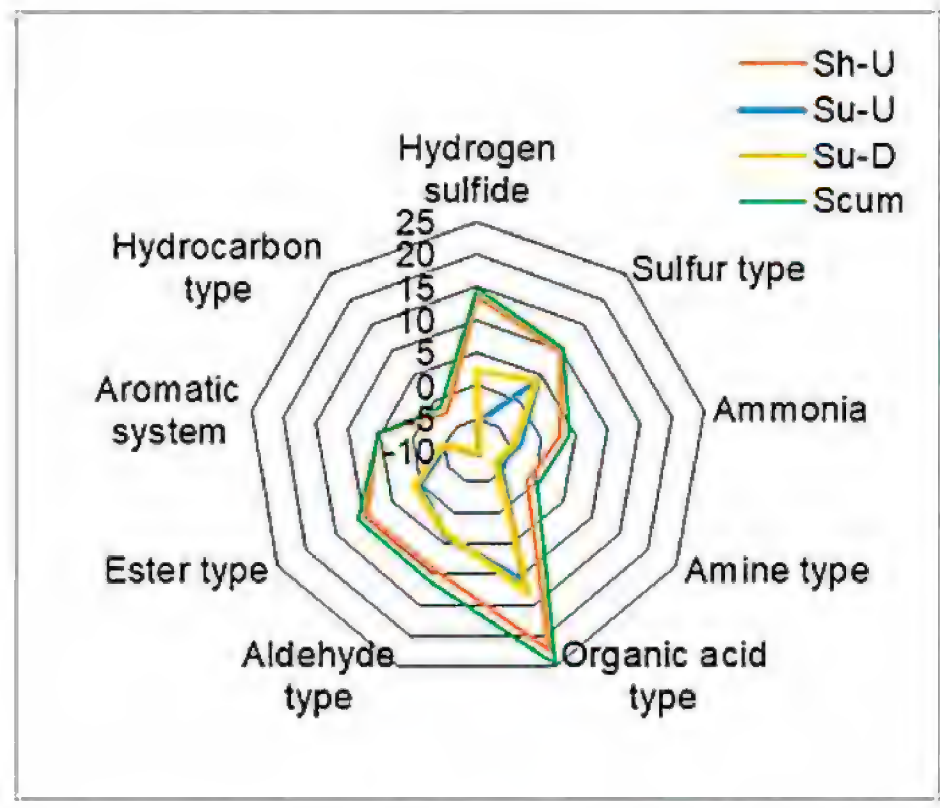


Figure 8. Strength of odor components from scum and sediments from Sh-U, Su-U and Su-D.

Conclusion

In this study, the water quality parameters and hydraulic phenomena were analyzed to determine their effect on odor and scum generation. The spatial and temporal variations in salinity at the confluence of the Sumida and Shakujii Rivers indicated that salt intrusion was prominent in both rivers 1 to 2 days after neap tide. Residual salinity may persist in the confluence,

pushed by the water pressure from Tokyo Bay during salinity intrusion. This resulted in two observed salinity peaks in one tidal cycle at the Shakujii River and upstream Sumida River, whereas only one salinity peak was observed at the downstream station of the Sumida River. The salinity intrusion in the Shakujii River was therefore influenced by the seawater from the downstream area of the Sumida River and the salinity retained in the deep point near the confluence. The DO level in the Shakujii River fluctuated significantly, while the Sumida River's DO level was affected by salinity intrusion from Tokyo Bay and freshwater from upstream tributaries. Low DO in the Shakujii River after rainfall may be attributed to organic matter decomposition. It was found that higher scum coverage appeared when DO levels were lower than 6 mg/L and salinity was below 1 psu. Scum generation was lower during neap tide than spring and intermediate tides. The electronic nose technology using an odor machine was used to analyze the odors of scum, sediment and water samples. The prominent odor components of scum were organic acids, and hydrogen sulfide. The foul odor may be caused by bottom sediment in the Shakujii River, which contains sulfur-rich organics from domestic wastewater and biomass decomposition. The prominent odor components of sediment in the Shakujii River were hydrogen sulfide (14.4%), organic acid (14.2%), ester (14%), sulfur (12.2%) and aldehyde (10.5%). In Sumida River sediments the prominent odor components were organic acid (4%), ester (3%), and sulfur (1%). The Shakujii River has a higher tendency to generate scum because its sediment odor index is higher, its sediment odor similarity with scum is higher, and salinity is lower than those of the Sumida River. This study recommends facilitating proper estuarine mixing and the transit of saltwater to diminish scum formation, with the possibility of improving river topography and strict implementation of sewer discharge controls, especially during rainfall periods.

Acknowledgements

The authors express sincere gratitude to Kita City Office, Tokyo for the data and cooperation. The authors also express special thanks to Dr. Kita of Shimadzu Corp. for valuable advice and suggestions about the use of the odor machine and analysis methodology.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Funding

This study was supported by the River Fund of The River Foundation, Japan. This research was supported in part by the project entitled "Study on guerrilla rainstorm, flood, and water pollution in megacity urban watersheds" funded by the Tokyo Metropolitan Government.

Author contributions

Conceptualization, J.C.C., R.O., K.Y.; methodology, J.C.C., R.O., K.Y.; software, R.O., K.Y.; validation, J.C.C., R.O., K.Y.; formal analysis, J.C.C., R.O., K.Y.; investigation, J.C.C., R.O., K.Y.; resources, K.Y.; data curation, J.C.C., R.O., K.Y.; writing—original draft preparation, J.C.C., R.O., K.Y.; writing—review and editing, J.C.C., R.O., K.Y.; visualization, J.C.C., R.O., K.Y.; supervision, K.Y.; project administration, K.Y.; funding acquisition, K.Y. All authors have read and agreed to the published version of the manuscript.

Author ORCIDs

Joan Cecilia Casila https://orcid.org/0000-0001-6319-8999
Katsuhide Yokoyama https://orcid.org/0000-0003-1576-6239

Data availability

All of the data that support the findings of this study are available in the main text.

References

Akcaalan R, Devesa-Garriga R, Dietrich, A, Steinhaus M, Dunkel A, Mall V, Manganelli M, Scardala S, Testai E, Codd GA, Kozisek F, Antonopoulou M, Ribeiro ARL, Sampaio MJ, Hiskia A, Triantis TM, Dionysiou DD, Puma GL, Lawton L, Edwards C, Andersen HR, Fatta-Kassinos D, Karaolia P, Combès A, Panksep K, Zervou S-K, Albay M, Köker L, Chernova E, Iliakopoulou S, Varga E, Visser PM, Gialleli AI, Zengin Z, Deftereos N, Miskaki P, Christophoridis C, Paraskevopoulou A, Lin T-F, Zamyadi A, Dimova G, Kaloudis T (2022) Water taste and odor (T&O): Challenges, gaps and solutions from a perspective of the WaterTOP network. Chemical Engineering Journal Advances 12: 100409. https://doi.org/10.1016/j.ceja.2022.100409

Arakawa T, Iitani K, Toma K, Mitsubayashi K (2022) Biosensors: Gas Sensors. In: Narayan R (Ed.) Encyclopedia of Sensors and Biosensors, 478–504. https://doi.org/10.1016/B978-0-12-822548-6.00066-2

Batterman S, Grant-Alfieri A, Seo SH (2023) Low level exposure to hydrogen sulfide: a review of emissions, community exposure, health effects, and exposure guidelines. Critical Reviews in Toxicology 53(4): 244–295. https://doi.org/10.1080/10408444.2023.2229925

Casila JC, Azhikodan G, Yokoyama K, Fukushima K, Terajima R (2017) Effect of Rainfall on Saltwater and Suspended Sediment Dynamics in Multi-branched Urban Tidal Estuaries. Journal of Japan Society of Civil Engineers, Ser. G (Environmental Res) 73: I_347–I_352. https://doi.org/10.2208/jscejer.73.I_347

Casila JC, Ella V, Yokoyama K (2019a) Effect of neap-spring hydrodynamics on salt and suspended sediment transport in multi-branched urban estuaries. Science of the Total Environment 694: 133653. https://doi.org/10.1016/J.SCITOTENV.2019.133653

Casila JC, Okuyama R, Yokoyama K (2019b) Hydrodynamic features , appearance of scum , and spatial distribution of odor in urban estuaries. Journal of Japan Society of Civil Engineers, Ser. G 75:I_141–I_146

Guo Q, Ding C, Xu H, Zhang X, Li Z, Li X, Yang B, Chen T, Wang C, Yu J (2021) Diagnosing complex odor problems occurring in micro-polluted source water: Primary approach and application. Environmental Pollution 271: 116373. https://doi.org/10.1016/j.envpol.2020.116373

Inagawa S, Asano K, Okuyama R, Casila J, Yokoyama K (2020) Physical Properties and Characteristics of Erosion and Deposition of Organic Sludge in Urban River Estuaries. Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering) 76(2): I_1291–I_1296. https://doi.org/10.2208/jscejhe.76.2_I_1291

Japan Meteorological Agency (2018) Japan Meteorological Agency. https://www.jma.go.jp/jma/index.html [Accessed 8 Aug 2018]

Japan River Restoration Network (JRRN) (2012) Restoration of Sumida River (Arakawa, Sumida, Taito Ward, Tokyo). http://www.a-rr.net/jp/en/waterside/domestic/07community_and_urban_river_re/570.html [Accessed 8 Jan 2019]

Kaneko M, Nihei Y (2012) Formation of Large-Scale Hypoxic Water Mass in Tidal Urban Rivers Due to Load of Combined Sewer Overflow. Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Eng) 68: I_1591–I_1596. https://doi.org/10.2208/jscejhe.68.I_1591

Kita J, Toko K (2014) Fragrance and flavor analyzer using odor deviation map. Sensors Mater 26:149–161. https://doi.org/10.18494/sam.2014.896

Ma H, Addy MM, Anderson E, Liu W, Liu Y, Nie Y, Chen P, Cheng B, Lei H, Ruan R (2016) A novel process for low-sulfur biodiesel production from scum waste. Bioresource Technology 214: 826–835. https://doi.org/10.1016/J.BIORTECH.2016.05.029

Ministry of the Environment (2019) Ministry of the Environment Olfactory Measurement Method Manual (In Japanese). http://www.env.go.jp/air/akushu/manual/manual_02.pdf [Accessed 23 Apr 2019]

Miura S, Ishikawa T, Hotta T (2017) Laboratory Experiment on Generation of Anaerobic Gas and Scum from Organic Sludge in Urban Rivers. Journal of Japan Society of Civil Engineers, Ser B1 (Hydraulic Eng) 73: I_1063–I_1068. https://doi.org/10.2208/jscejhe.73.I_1063

Miura S, Ishikawa T, Hotta T (2018) Laboratory experiment on generation of anaerobic gas and scum from organic sludge in urban rivers. In: Water pollution. XIV. WIT Press, 9–20.

Müezzinoğlu A, Sponza D, K Ken I, Alparslan N, Akyarli A, Zt Re N (2000) Hydrogen Sulfide and Odor Control in İzmir Bay. Water, Air, & Soil Pollution 123: 245–257. https://doi.org/10.1023/A:1005219405638

Muñoz R, Sivret EC, Parcsi G, Lebrero R, Wang X, Suffet IHM, Stuetz RM (2010) Monitoring techniques for odour abatement assessment. Water Research 44: 5129–5149. https://doi.org/10.1016/J.WATRES.2010.06.013

Murat A, Méar Y, Poizot E, Dauvin JC, Beryouni K (2016) Silting up and development of anoxic conditions enhanced by high abundance of the geoengineer species *Ophiothrix fragilis*. Continental Shelf Research 118: 11–22. https://doi.org/10.1016/J.CSR.2016.01.003

Nagappan PG, Subramaniam S, Wang DY (2017) Olfaction as a soldier-- a review of the physiology and its present and future use in the military. Military Medical Research 4: 9. https://doi.org/10.1186/s40779-017-0119-4

Nihei Y, Yamaguchi H, Kashiwada J (2009) DO Environments in Tidal Rivers with Massive Fish Death. Journal of Japan Society of Civil Engineers, Ser. B2 (Coastal Eng) 65: 1021–1025. https://doi.org/10.2208/kaigan.65.1021

Okuyama R, Terajima R, Casila JC, Yokoyama K (2018) Temporal variation of salinity, DO, SSC and Fundamental property of odor in the confluence of Shakujii and Sumida Rivers. Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Eng) 74: I_541–I_546

Pandan MA, Naddeo V, Zarra T, Belgiorno V, Ballesteros Jr F (2017) Odour emission capacity as a surrogate parameter for the assessment of river water quality. WIT Transactions on Ecology and the Environment 221: 43–50. https://doi.org/10.2495/RBM170051

Qiu S, Hou P, Huang J, Han W, Kang Z (2021) The Monitoring of Black-Odor River by Electronic Nose with Chemometrics for pH, COD, TN, and TP. Chemosensors 9(7): 168. https://doi.org/10.3390/chemosensors9070168

Rahman S, Alwadie AS, Irfan M, Nawaz R, Raza M, Javed E, Awais M (2020) Wireless E-nose sensors to detect volatile organic gases through multivariate analysis. Micromachines 11(6): 597. https://doi.org/10.3390/mi11060597

Sado-Imamura Y, Fukushi K (2018) Considering water quality of urban rivers from the perspectives of unpleasant odor. Sustainability 10(3): 650. https://doi.org/10.3390/su10030650

Somsook K, Duka MA, Olap NA, Casila JCC, Yokoyama K (2020) Direct measurement of secondary circulation in a meandering macrotidal estuary. Science of The Total Environment 739: 139503. https://doi.org/10.1016/j.scitotenv.2020.139503

Sun X, Wang Y, Li H, Yang X, Sun L, Wang X, Wang T, Wang W (2016) Organic acids in cloud water and rainwater at a mountain site in acid rain areas of South China. Environmental Science and Pollution Research 23: 9529–9539. https://doi.org/10.1007/s11356-016-6038-1

Taniguchi T (1999) Changes in water quality of the Sumida River in Tokyo from 1900 to 1960 estimated literary works. Science reports of the Tohoku University. Series 7, Geography 49: 227–232.

Uncles RJ (2002) Estuarine physical processes research: Some recent studies and progress. Estuarine, Coastal and Shelf Science 55: 829–856. https://doi.org/10.1006/ECSS.2002.1032

Wang Y, Feng S, Bai X, Zhao J, Xia S (2016) Scum sludge as a potential feedstock for biodiesel production from wastewater treatment plants. Waste Management 47: 91–97. https://doi.org/10.1016/J.WASMAN.2015.06.036

Wang Y, Yan X, Wang S, Gao S, Yang K, Zhang R, Zhang M, Wang M, Ren L, Yu J (2023) Electronic nose application for detecting different odorants in source water: Possibility and scenario. Environmental Research 227: 115677. https://doi.org/10.1016/j.envres.2023.115677

Wu H, Wu X, Rovelli L, Lorke A (2024a) Dynamics of Microcystis surface scum formation under different wind conditions: the role of hydrodynamic processes at the air-water interface. Frontiers in Plant Science 15: 1370874. https://doi.org/10.3389/fpls.2024.1370874

Wu H, Wu X, Rovelli L, Lorke A (2024b) Selection of photosynthetic traits by turbulent mixing governs formation of cyanobacterial blooms in shallow eutrophic lakes. The ISME Journal 18(1): wrae021. https://doi.org/10.1093/ismejo/wrae021

Xu J, Zhang M, Xie P (2007) Stable carbon isotope variations in surface bloom scum and subsurface seston among shallow eutrophic lakes. Harmful Algae 6:679–685. https://doi.org/10.1016/J.HAL.2007.02.002